Space Cryomagnetics

Technical Report

| Item: | **Loss of Vacuum and Venting from the AMS-02 Cryostat** | Author: | **S M Harrison** |
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# 1 Introduction

The AMS-02 superconducting magnet cryostat contains a cryogenic vessel holding up to 2500 litres of superfluid liquid helium at a temperature of approximately 1.8 K (-271.35 C). If liquid helium at this temperature is converted to gas at room temperature and pressure (295 K, 1.01325 bar) the volume increases by a factor of 880, so the presence of such a large quantity of cryogenic liquid is considered potentially hazardous.

This report describes the development which has been undertaken to demonstrate that the AMS-02 cryogenic system is safe on the ground at the Kennedy Space Center – and in the Space Shuttle – under all conceivable modes of operation and fault conditions.

# 2 Basis of the Hazard

Superfluid helium has very high specific heat capacity so it takes a great deal of energy to increase its temperature. The power required for rapid warming can generally only be generated from two sources: either by quenching of a superconducting magnet immersed in the helium, or by a leak into the vacuum chamber which normally insulates the helium vessel. In the case of AMS-02, the superconducting magnet is entirely separate from the helium tank and is cooled by conduction, so a magnet quench cannot dissipate energy rapidly into the helium. (In addition, the magnet will never be energised inside the Shuttle.) However, there are some circumstances under which a rupture or leak of the vacuum case may be credible.

## 2.1 Insulation of Liquid Helium Vessels

Effective insulation of cryogenic tanks is always required to reduce the heat transfer from ambient temperature surroundings to the cold surfaces. This makes long-term storage of the cryogen feasible, and it prevents condensation or ice formation on components exposed to the atmosphere. Cryogenic insulation uses some combination of vacuum (to eliminate convection and conduction), radiation shields and multi-layer insulation (MLI) to reduce radiation.

## 2.2 Vacuum Leak

If a hole appears in the vacuum vessel, air begins to leak into the vacuum chamber. Because the pressure inside the vacuum case is so low, the air flow is choked in the hole and the rate of ingress is limited. What happens subsequently depends on the size of the hole and the cold surface area. If the hole is relatively small and the cold surface area is large, all the incoming air will freeze on the cold surface (this process is usually called "cryopumping"). The air gives up its latent heat and warms the cryogen, but the vacuum pressure remains very low because the cryopumping removes all the air from the vacuum space. However, if the hole is large enough (or the cold surface area is small) the air will enter the vacuum space faster than it can be removed by cryopumping. In this case the vacuum will be degraded, and convective heat transfer will be added to the heat load due to freezing and condensation of the air.

## 2.3 Catastrophic Loss of Vacuum

The worst conceivable fault scenario for any cryogenic system is a catastrophic loss of the insulating vacuum. This is what happens after a large hole (several inches in diameter) is suddenly punched in the vacuum vessel. Air rushes through the hole so quickly that any cryopumping is overwhelmed and the vacuum chamber quickly rises to atmospheric pressure.

# 3 Defining the Fault Scenarios

Two different fault scenarios have been defined for the AMS-02 magnet system, one for ground processing and the other for launch pad operations. (All possible landing scenarios were also considered, but none presented hazards as serious as launch.)

## 3.1 Loss of Vacuum During Ground Processing

During ground processing, the vacuum case could be punctured as a result of a major accident such as a collision with a vehicle or another unlikely mishap. For all ground operations, therefore, a catastrophic loss of vacuum - as defined in Section 2.3 above – has to be considered.

## 3.2 Vacuum Leak in the Shuttle Bay

Once the magnet is inside the Space Shuttle, a major incident such as a collision is no longer considered credible. The following text is from an e-mail sent by Ken Bollweg of Lockheed Martin on 20 September 2001, and it summarises the procedure agreed with NASA.

> *"A meeting was held on September 5, 2001 at JSC to discuss the status of the AMS-02 Helium Vent Tests at Space Cryomagnetics Ltd. (SCL) and to establish further test and analyses plans. Attendees included Rick Miller, Brad Harris, Mark Fields, Ray Serna, Jim Bates, Rick Sanchez, Daniel Newswander, Doug Cline, Trent Martin, Phil Mott, and myself . (Details on this meeting are included in Trent Martin's e-mail dated September 6th below.) Jim Bates and I then followed up with Dave O'Brien (PSRP Chair) on September 5th as well.*
>
> *It was agreed that there is no credible scenario that could lead to a sudden loss of vacuum in the AMS-02 Cryomagnet Dewar after the Orbiter payload bay doors were closed and prior to launch. The temperature of the Superfluid Helium (SFHe) Tank and pressure of the SFHe Tank as well as pressure of the Cryomagnet Vacuum Case (VC) will be monitored until Launch minus 9 minutes. At that time a go/no-go call on the status of the cryogenic systems will be made by AMS. The requirements for the frequency of measurements, number of sensors, etc. are still TBD.*

*The following leak scenario was worked out with Dave O'Brien on September 5th and reviewed with Bill Manha on September 17th:*

*There are two large O-ring seals (~9 ft. diameter x ¼ inch diameter cross-section) at each of the four joints between the VC Outer Cylinder to Support Rings and Support Rings to the Conical Flanges; i.e. 8 large O-rings in all. There are several other dual O-rings throughout the hardware but they are much smaller (< 6 inches). We will consider two large O-rings to be pinched at assembly and that the pinches are right next to each other on the same joint. Both "pinches" will be ~3 inches long but will not be detected during initial leak tests on the individual O-rings using the test ports between the seals. We will then assume that it is determined (via the test ports) that one of them is leaking at the launch pad. It would be a monumental undertaking lasting SEVERAL months to disassemble the entire experiment, grind out the welds on the VC, open it up, repair the leaking O-ring(s), reassemble the Cryomagnet and re-weld the VC, reassemble the entire experiment, and recalibrate it. Obviously, we would argue against the need to do this.*

*So, we will then assume the second pinched O-ring starts leaking due to vibrations from SRB ignition at launch. Using the assumption that the leak path is ~3 inches long by the maximum gap we could possibly have gives us the maximum equivalent hole we should use in the next small dewar vent tests. This is still quite conservative since a very narrow, long, deep hole will never allow as much flow as a round, shallow hole of the same area.*

*Therefore, if the maximum gap is 0.001 inch, the area is 0.003 square inches, which is the equivalent area of a ~0.062 inch diameter hole. A 0.001" gap with 192 bolts at ~1¾ inch spacing is highly unlikely since the flanges will be in direct contact with each other and can be inspected. However, this will be assumed for the next small dewar vent test. For the last test, an even more unrealistic 0.003 inch gap will be assumed. This is the equivalent of a ~0.107 inch diameter hole. Both these hole sizes will be scaled down from the full-scale flight SFHe Tank (~2500 liters) geometry to the small dewar SFHe Tank (~15 liters) used in the vent tests. In these tests, there will be no insulation on the small dewar SFHe Tank. If successful, the flight SFHe Tank will be insulated with four vapor-cooled shields and ~200 layers of MLI. There would be no Cryocoat or other insulation on it.*

*Keep in mind, that the burst disks and ground vent plumbing still must be sized and designed to adequately protect the system against over-pressure and personnel exposure during all phases of ground processing at all sites."*

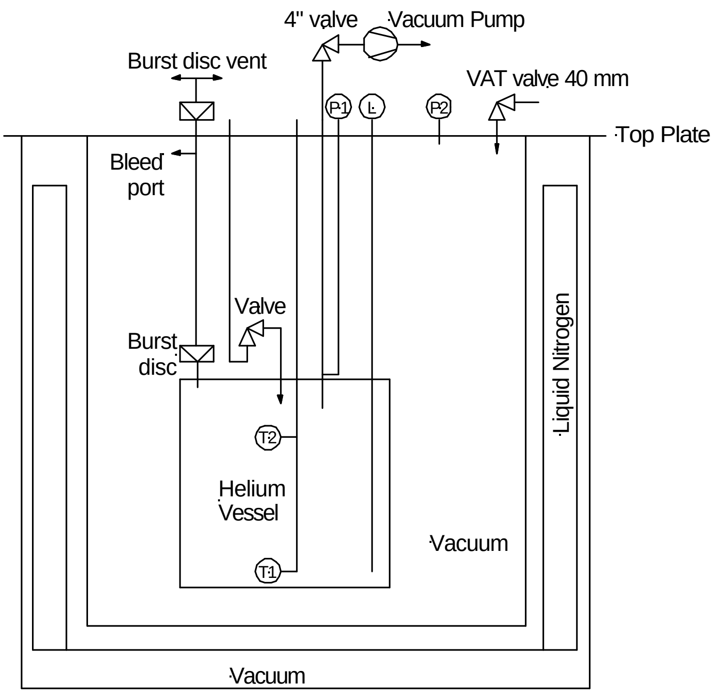


Figure 1

This procedure has been followed, with the single exception that Cryocoat insulation is now to be applied to the magnet superfluid helium vessel for reasons outlined below. Accordingly, the tests on the small dewar have been performed with this same insulation, prepared and applied in the same manner.

# 4 Venting Demonstration Test Rig

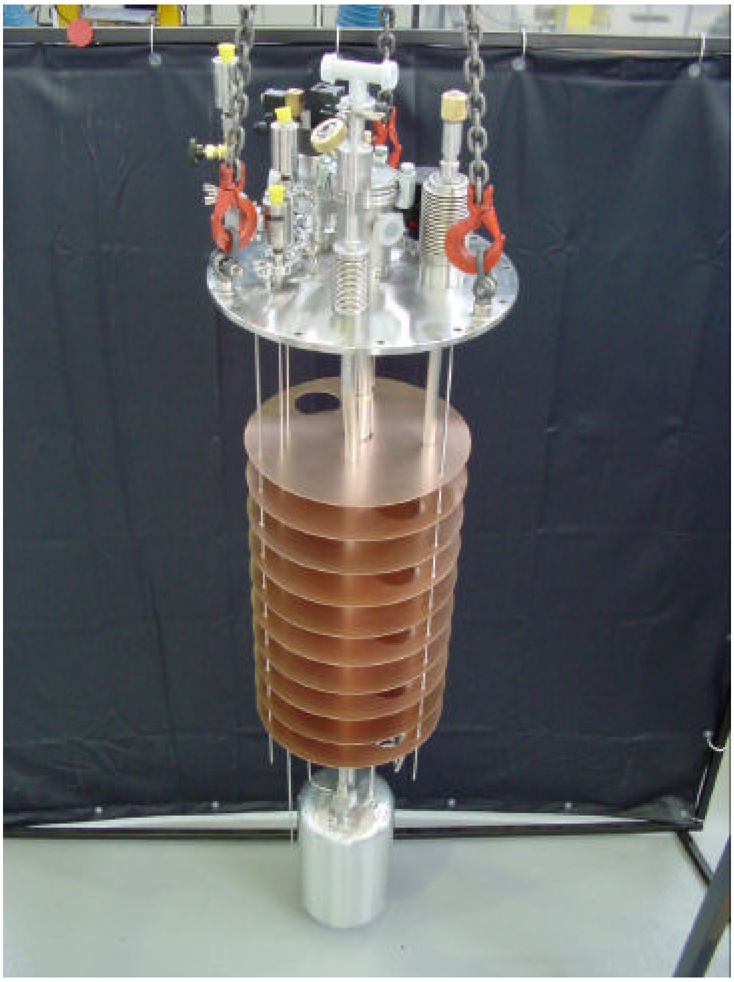

Figure 2

The venting demonstration test rig (VDTR) is shown schematically in Figure 1, and a picture of the test insert is given in Figure 2. The VDTR consists of a stainless steel vessel containing the superfluid helium. The vessel is suspended from a top plate by a neck tube, 40 mm in diameter, which allows the vapour pressure of the helium to be lowered so that the temperature can be reduced from 4.2 K (the boiling point at atmospheric pressure) to 1.8 K. The thin copper discs visible in Figure 2 are radiation baffles, which reduce the transfer of heat from the top plate - at room temperature - to the cold helium. The test insert is mounted inside a bucket test dewar. This is a cylindrical volume, 350 mm in diameter, which can be evacuated. It can be cooled with liquid nitrogen, which means that the test volume is normally under vacuum, with the walls at approximately 80 K. (The walls have to be cooled, otherwise the radiant heat load from room temperature would be so high that it would be impossible to collect liquid helium in the system. In the real AMS magnet, this function is achieved with MLI and radiation shields, but these would provide additional insulation following loss of vacuum, as well as extended surfaces for cryopumping, so the test arrangement is conservative.) The test volume can be opened to atmosphere through a 40 mm diameter, fast-acting valve. Different orifices can be positioned in series with the valve to control the rate of air ingress: with no orifice, the 40 mm hole is large enough to simulate a catastrophic rupture of the vacuum vessel.

# 5 Vacuum Leak Tests

A set of three tests is required: one for each of the hole sizes required plus one with no hole at all to measure the background heating due to the test rig alone. This background heat load should be relatively much larger for the test rig owing to its small size and because it is not so thoroughly optimised for thermal performance as the AMS magnet system.

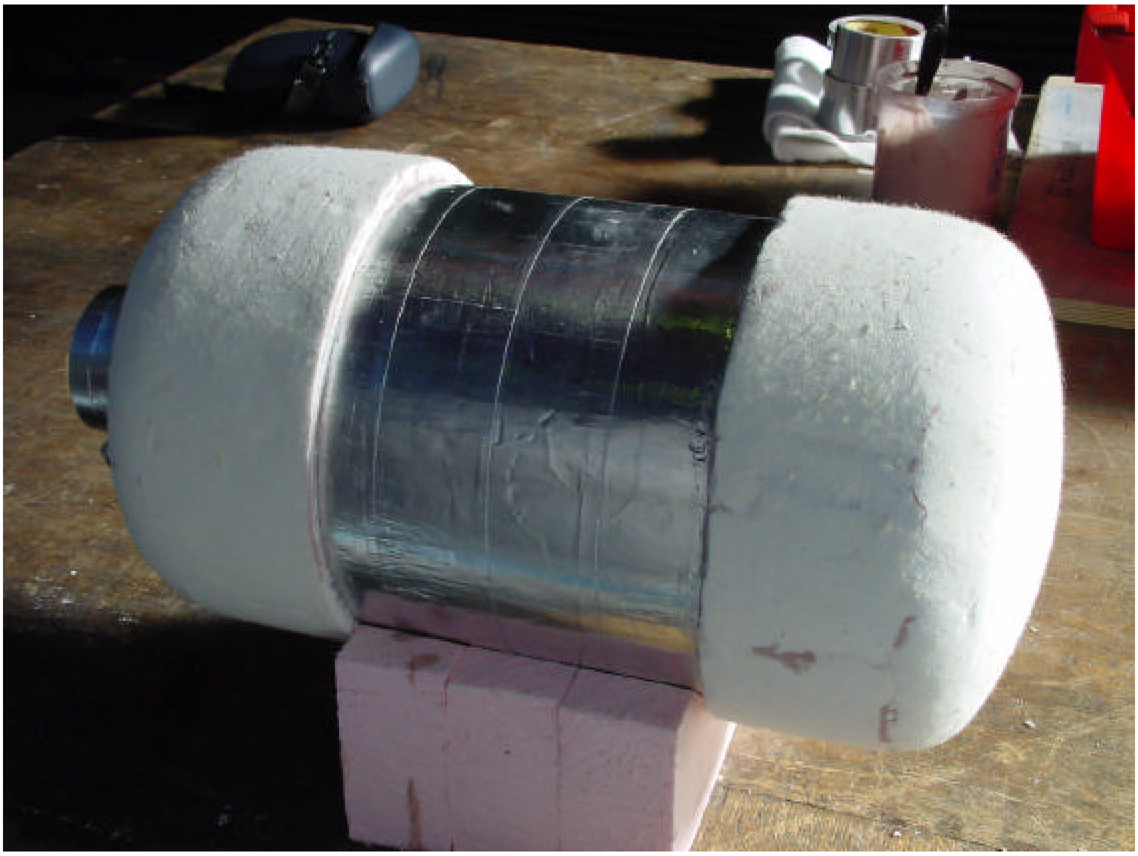

Figure 3

## 5.1 Insulation

The helium tank for the AMS magnet will be insulated using a proprietary system called "Cryocoat Ultralight", manufactured by Composite Technology Development (CTD) of Lafayette, Colorado. The insulation is produced in the form of 3 mm thick tiles with dimensions up to 300 mm x 300 mm. The tiles are conformable when first applied to the tank, but cure at room temperature after about 24 hours. Because the insulation may have an effect following a vacuum leak, identical tiles have been used to insulate the test vessel.

Another important feature of the insulation is that it should help to make the test vessel geometrically as similar as possible to the magnet system. Because the volume in the VDTR is about 200 times less than in the magnet helium vessel, the surface area to volume ratio of the VDTR is much bigger, even though the magnet helium vessel is toroidal rather than cylindrical. This could potentially distort the experimental results, since a large A/V ratio could make cryopumping in the VDTR more effective than in the magnet system. Additional insulation, to a thickness of 15 mm, has therefore been added to parts of the

VDTR vessel to control precisely the surface area over which cryopumping can take place (see Figure 3). The neck tube is also thickly insulated for the same reason. The thinly insulated area to volume ratio of the VDTR vessel is thus the same as the total A/V ratio of the magnet system helium vessel.

## 5.2 Hole Size Determination

Calculations show that the hole sizes under consideration are sufficiently small that virtually all the air entering the vacuum space will be cryopumped onto the cold surfaces. Under these circumstances, the heat given up to the helium will be directly proportional to the flow rate of air. Since the air ingress must be choked, the flow rate will be directly proportional to the cross-sectional area of the hole. It follows that if

$$\frac{A_{VDTR}}{V_{VDTR}} = \frac{A_{AMS}}{V_{AMS}}$$

where $A$ is the area of the hole and $V$ is the volume of superfluid helium then the rate of pressurisation of the helium should be identical in both cases. Given that the background heat load in the test vessel is relatively much higher than in the magnet vessel, and that the radiation shields and MLI in the magnet system provide considerable additional cryopumping compared with the VDTR, tests conducted using these ratios for the VDTR must actually be conservative. That is, the VDTR will pressurise more quickly than the AMS magnet system.

The surface area and volume of the AMS magnet helium vessel are 19 $m^2$ and 2460 litres respectively. The corresponding area and volume of the VDTR vessel are 0.106 $m^2$ and 13.8 litres, to give the same A/V ratio in each case.

## 5.3 Test Procedure

The procedure in each of the tests was the same. The vessel was filled with normal liquid helium boiling at 4.2 K. The temperature was reduced by pumping on the vapour above the liquid. By repeated filling and pumping cycles the vessel was filled with superfluid helium at around 1.6 K. The liquid level was monitored by a standard helium liquid level probe but, for better accuracy, the actual mass of helium inside the vessel was calculated from the change in mass (the whole VDTR is suspended from a load cell). Valves were then used to isolate the vessel, and the pressure and temperature inside were monitored. In the case of the two tests using orifices to simulate leaks, the vent valve was opened to admit air into the vacuum space. The purpose of the other test was simply to measure the background effect of the test rig itself, so the vent valve remained closed throughout. When the pressure in the tank reached about 4 bar, another valve was opened to vent the helium space.

| MODEL HOLE DIAMETER | FULL SIZE HOLE DIAMETER | FULL SIZE O-RING GAP |
|---|---|---|
| 0.12 mm<br>0.0047 inch | 1.60 mm<br>0.063 inch | 0.0264 mm x 76.2 mm<br>0.00104 inch x 3 inch |
| 0.21 mm<br>0.0083 inch | 2.79 mm<br>0.110 inch | 0.0810 mm x 76.2 mm<br>0.00319 inch x 3 inch |

The orifices were made by laser drilling stainless steel vacuum blanks then accurately measuring the hole diameters. The two holes used were 0.12 mm and 0.21 mm in diameter. Using the analogy in Section 3.2 above, the equivalent gaps where the O-rings are pinched are 0.00104 and 0.00319 inches respectively, slightly exceeding the agreed maximum gap sizes in the full size vacuum case. The correlation between hole sizes in the test facility (model) and the full size vacuum case is summarised in Table 1.

## 5.4 Test Results

Figures 4 and 5 show the temperature and pressure in the helium tank for the three experiments. Zero time for the two experiments with orifices was taken as the instant when the vacuum vent valve was opened. Zero time for the calibration test was taken to give a start temperature close to the zero time temperatures of the other tests.

On the pressure plots, there is an abrupt change of slope at 1200 s, 2600 s and 4000 s for the 0.21 mm hole, 0.12 mm hole and no hole cases respectively. These correspond to points of inflexion on the temperature plots, and mark the transition of the helium from the superfluid to the normal state. The depressurisation can be seen on all the pressure plots when the pressure was between 3.5 and 4.5 bar: what is of interest is the time taken to reach 3 bar, as this is the set pressure for the burst discs on the AMS helium vessel. (Note that the actual maximum pressures reached in the three tests were different: this is because the pressure was released manually rather than waiting for a set of burst discs to be destroyed in each case.) The effect of the depressurisation can also be seen on the temperature plots as a sudden drop in temperature. In the case of the 0.21 mm hole, it can be seen that the temperature then recovers to 4.2 K and the helium continues to boil at atmospheric pressure.

- With no vacuum vent hole, the helium pressure reached 3.0 bar after 6440 s.
- With a 0.12 mm vent hole, equivalent to a double O-ring pinch 3 inches long and 0.00104 inches across, the helium pressure reached 3.0 bar after 4930 s.
- With a 0.21 mm vent hole, equivalent to a double O-ring pinch 3 inches long and 0.00319 inches across, the helium pressure reached 3.0 bar after 2590 s.

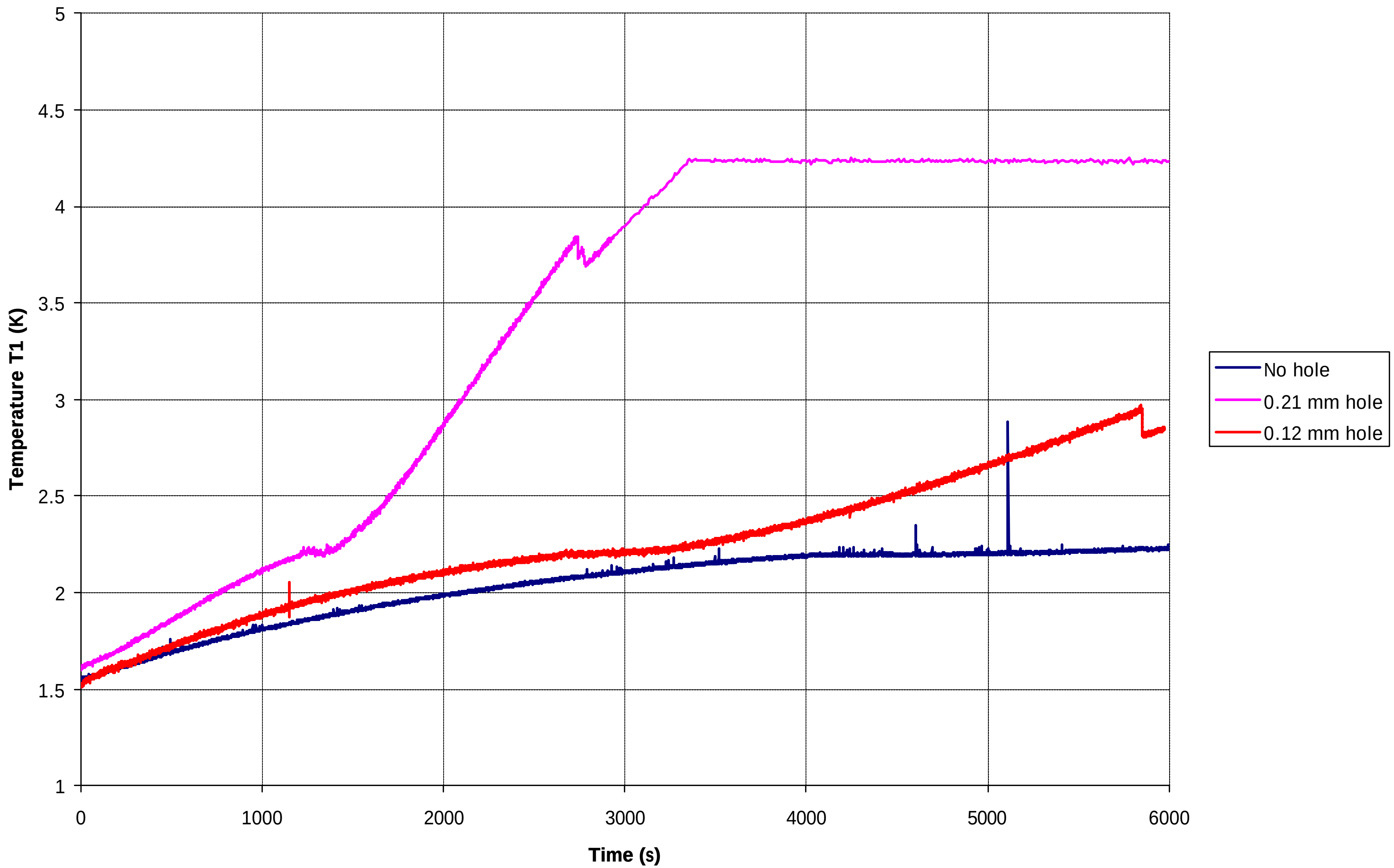
Temperature T1 (K)
5
4.5
4
3.5
3
2.5
2
1.5
1
0
1000
2000
3000
4000
5000
6000
Time (s)
No hole
0.21 mm hole
0.12 mm hole

Figure 4

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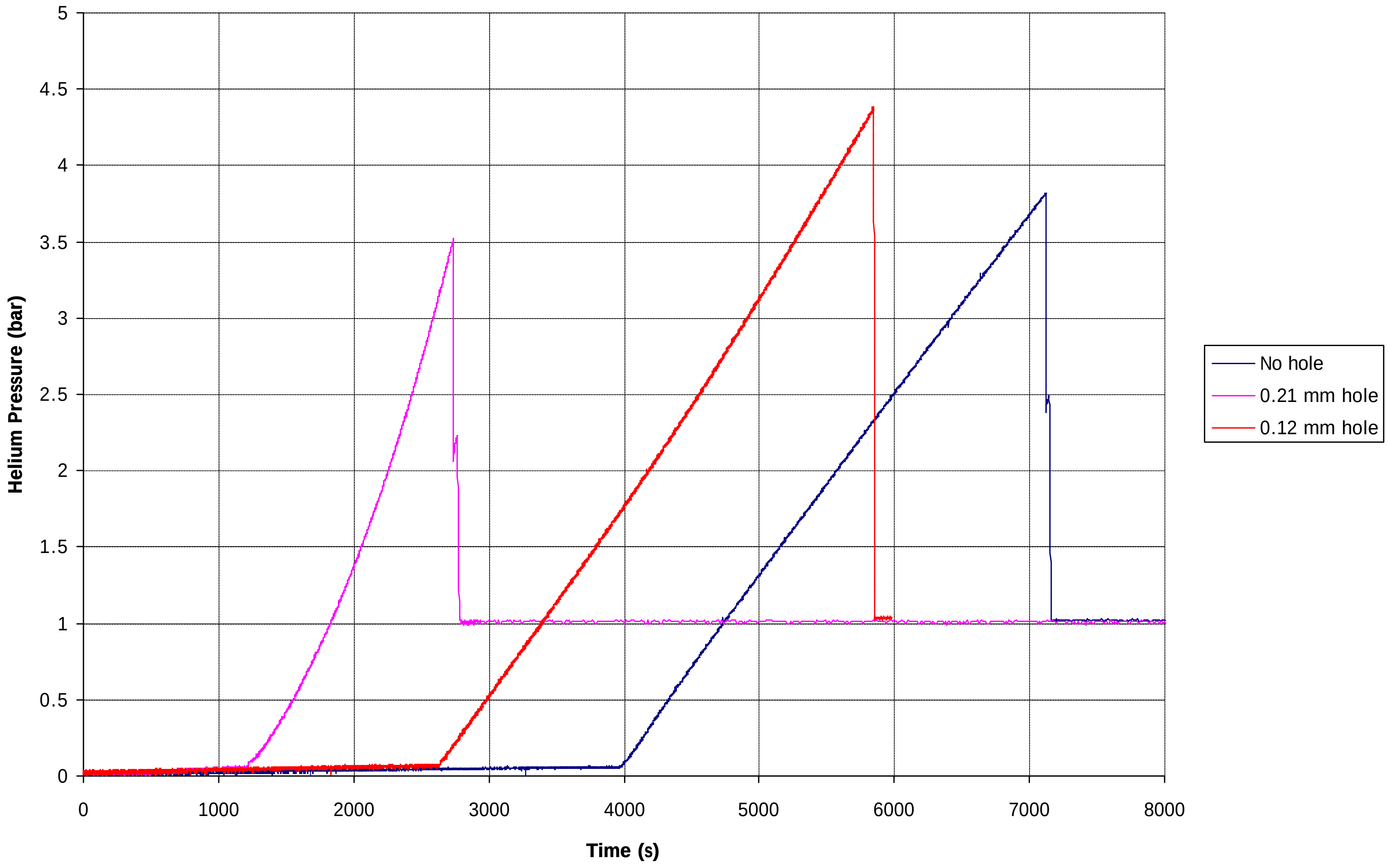

5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Helium Pressure (bar)
0
1000
2000
3000
4000
5000
6000
7000
8000
Time (s)
No hole
0.21 mm hole
0.12 mm hole


Figure 5

## 5.5 Discussion

The results above give an indication of the time taken for venting of the helium tank to begin after launch, following the severe damage to the O-rings postulated in Section 3.2 above. The analysis is conservative (times to vent are too short) because:

- The real AMS system has around 200 layers of MLI and four vapour-cooled radiation shields which would increase cryopumping and reduce any residual convection;
- The background losses in the real AMS should be two orders of magnitude lower (relative to helium volume) than in the VDTR, so all times to vent should be much longer.

Two remaining variables are the liquid level in the system at launch, and the exact temperature of the helium. If AMS was launched without the helium vessel being full the helium would warm up to the superfluid/normal liquid transition more quickly. Once through that transition, however, the rate of pressure rise would be lower because of the larger gas volume. The helium temperature in the tests was initially 1.6 K: it could be higher on the launch pad. Again the result would be that the helium reached the superfluid/normal liquid transition more quickly, but pressurisation above this point would proceed as in the tests.

Both these scenarios are very unlikely: the last operation carried out on AMS is a superfluid helium top-off on the launch pad, and the system is flown with a vent pump which pumps on the helium (keeping the temperature down) until 9 minutes before launch. Even if the worst case applied, and the magnet was launched at a temperature close to 2.2 K, the pressurisation curves indicate the times taken to reach 3.0 bar and vent the helium tank as follows.

- With no vacuum leak (VDTR baseline) 2440 s.
- With a 0.12 mm vent hole, equivalent to a double O-ring pinch 3 inches long and 0.00104 inches across, 2330 s.
- With a 0.21 mm vent hole, equivalent to a double O-ring pinch 3 inches long and 0.00319 inches across, 1390 s.

## 5.6 Conclusion

With all the following simultaneous faults

- Two of the vacuum case O-rings leak at the same position
- The gap between the vacuum case flanges is 0.003 inches
- The leak was not detected during the 12+ months between magnet integration and launch
- The second leak begins to admit air only at the instant of launch
- The MLI and vapour-cooled radiation shields on the magnet system have no effect
- The background heat load on the magnet system is more than 200 times worse than expected
- The system is launched partially full or at an elevated temperature

the helium tank will not pressurise sufficiently to vent the helium for 23 minutes after launch.

# 6 Catastrophic Loss of Vacuum (Ground Operations Only)

In addition to the vacuum leak tests carried out to determine the behaviour of the AMS system in the event of a leak in the vacuum case at launch, considerable development has been undertaken to determine what would happen in the event of a serious accident during ground operations which resulted in a major breach of the vacuum case. The results of the experiments and analysis were compiled in a paper "Loss of Vacuum Experiments on a Superfluid Helium Vessel" which was accepted for publication by the US Institute of Electrical and Electronics Engineers (IEEE) after peer review.

In brief, the research concluded that the heat flux to superfluid helium contained in an uninsulated tank increases to a level of approximately 31 $kW/m^2$ and then remains constant until the helium tank is vented through burst discs. Applying a 3 mm thickness of the Cryocoat Ultralight insulation reduced that heat flux by a factor of seven to 4.4 $kW/m^2$. Knowing the surface area and volume of the vessel, this heat flux was used to determine the calculate of pressure rise in the helium by isochoric heating until the burst disc ruptured. Once the relief path was open, classical compressible flow theory was used to calculate the venting rate of helium from the vessel to the environment. The thermodynamic energy equation was used, together with the venting rate, to calculate the pressure and temperature in the vessel as the helium continued to vent.

There was very close correlation between the results predicted from the calculations and those measured in the experiments (see the above referenced paper). The same technique has therefore been used to determine the required burst disc size on the magnet system. The calculation shows that the burst disc area required is 1520 $mm^2$, and this has been increased by 5% to 1590 $mm^2$ to give some additional margin.

The burst discs themselves are designed with intrinsic redundancy, that is there are two bursting mechanisms for each disc (a reverse buckling membrane with a peripheral score line and cutting teeth). This means that a single vent path is sufficient: there is no need for redundant burst discs. The design and arrangement of the burst discs have been provisionally approved by the PSRP, and will be subject to final approval at the Phase 2 safety review.

**S M Harrison**
**11 December 2002**